NuSOnG:

Looking for Heavy and Light New Physics in Neutrino Scattering

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Fermilab Wine & Cheese

based on

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∼ 36 authors

∼ 7 theorists

16 institutions

(including FNAL, ANL, LANL)

Terascale Physics Opportunities at a High Statistics, High Energy Neutrino Scattering Experiment: NuSOnG
Final Draft

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This article presents the physics case for a new high-energy, ultra-high statistics neutrino scattering experiment, NuSOnG (Neutrino Scattering on Glass). This experiment uses a Tevatron-based neutrino beam to obtain over an order of magnitude higher statistics than presently available for the purely weak processes $\nu_\mu + e^- \to \nu_\mu + e^-$ and $\nu_\mu + e^- \to \nu_e + \mu^-$. A sample of DIS events which is over two orders of magnitude larger than past samples will also be obtained. As a result, NuSOnG will be unique among present and planned experiments for its ability to probe neutrino couplings to Beyond the Standard Model physics. Many Beyond Standard Model theories physics predict a rich hierarchy of TeV-scale new states that can correct neutrino cross-sections, through modifications of $Z\nu\nu$ couplings, tree-level exchanges of new particles such as Z's, or through loop-level oblique corrections to gauge boson propagators. These corrections are generic in theories of extra dimensions, extended gauge symmetries, supersymmetry, and more. The sensitivity of NuSOnG to this new physics extends beyond 5 TeV mass scales. This article reviews these physics opportunities.

Outline

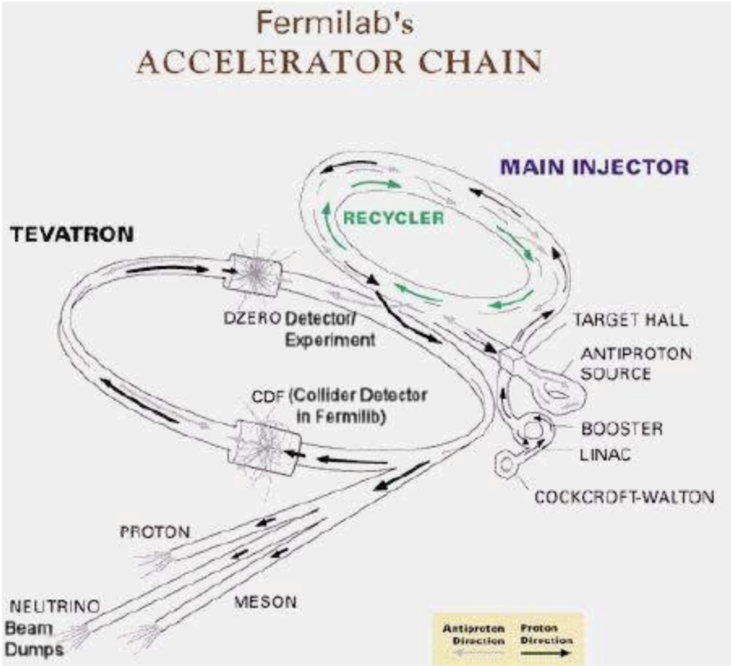
1. Neutrino Scattering on Glass – a Tevatron Based Neutrino Fixed Target Scattering Experiment;
2. The Physics of Neutrino – Charged Fermion Scattering;
3. Neutrino – Electron Scattering and New Physics;
4. Some TeV-Scale Examples. NuSOnG –LHC Interplay;
5. The Neutrino Coupling to the Z-Boson;
6. New 'Sterile" Fermions and Other "Light" Physics;
7. Concluding Thoughts.

1. Neutrino Scattering On Glass

NuSOnG is a proposal to study fixed-target neutrino – matter interactions

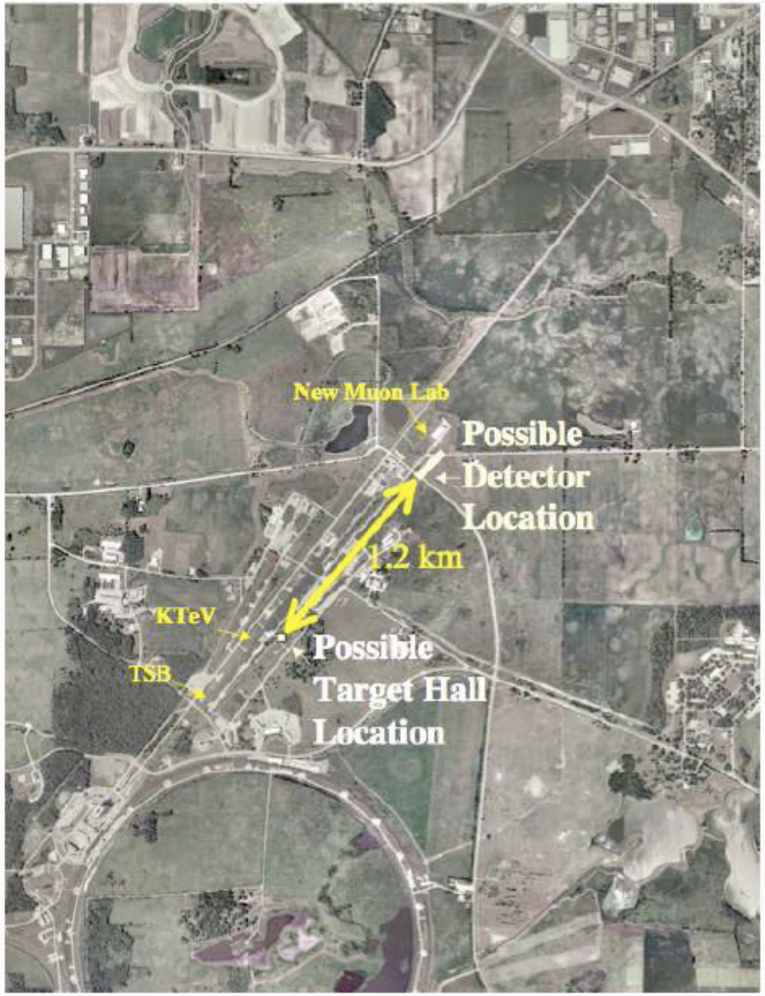
- High Energies – protons from the Tevatron
- High Statistics – lots of protons from the Tevatron, large detector
- "Rare" Processes – highly segmented detectors capable of "seeing" electrons
- Well Understood Neutrino Flux – "ratio-like" measurements

NuSOnG will use 800 GeV Protons from the Tevatron



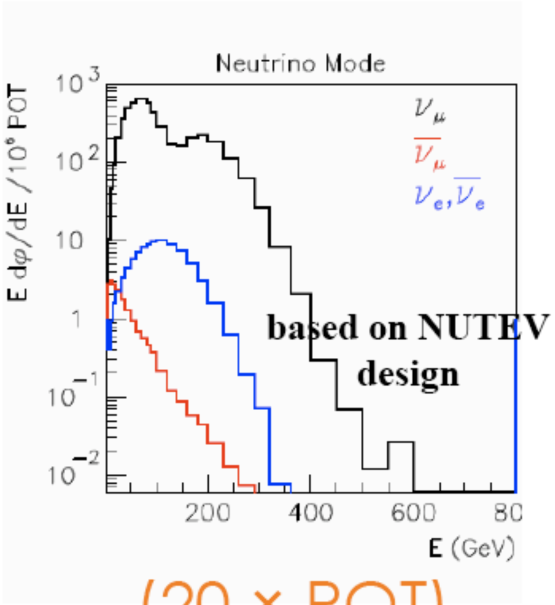
This requires the TeVatron to achieve new records:

5× the number of protons per fill,
1.5 × faster cycle time,
66% uptime per year



[but it doesn't need any antiprotons...]

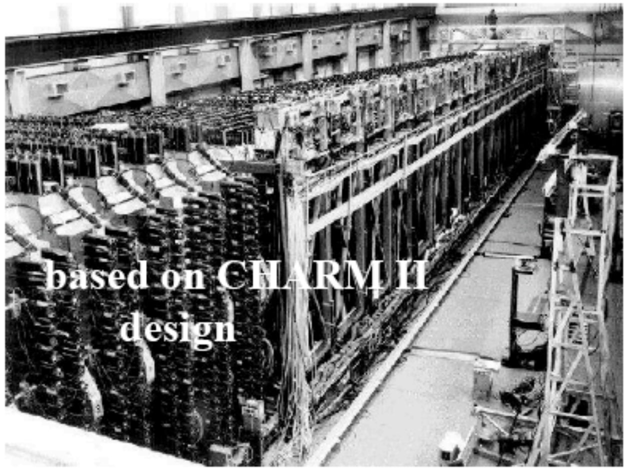
High-energy, very flavor-pure neutrino beam



(20 × POT)

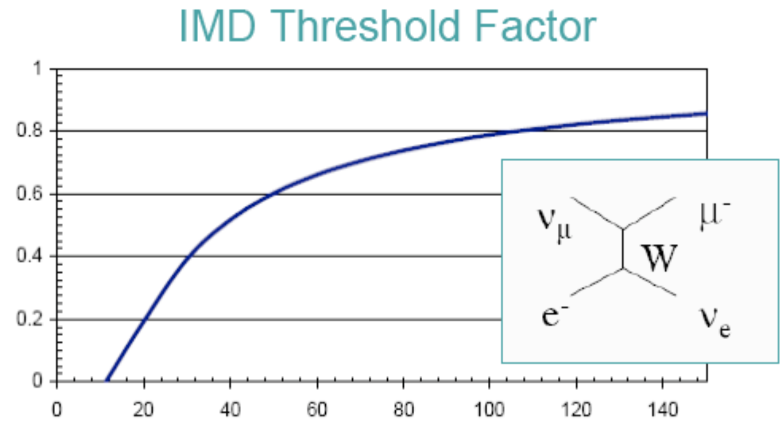
×

Well-segmented, massive detector

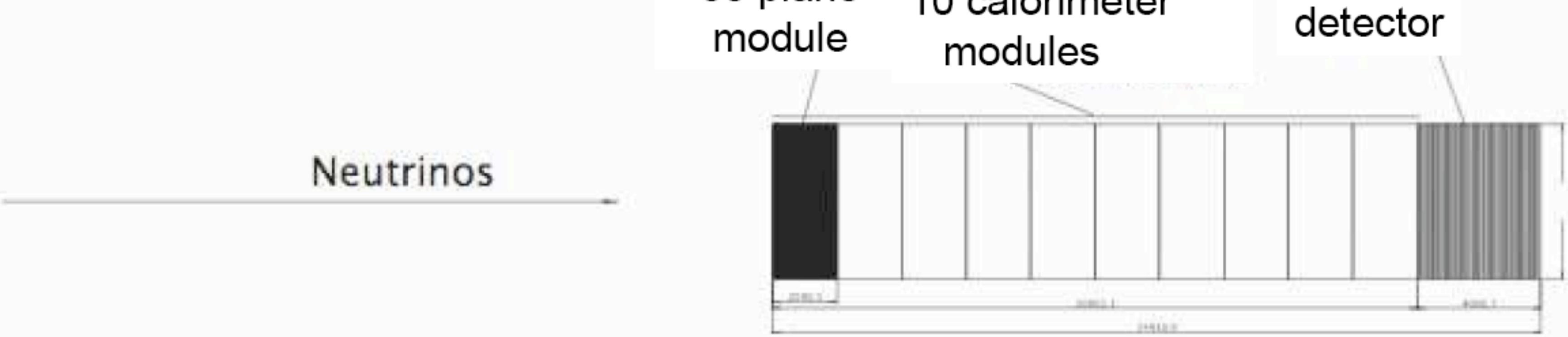


(6 × mass)

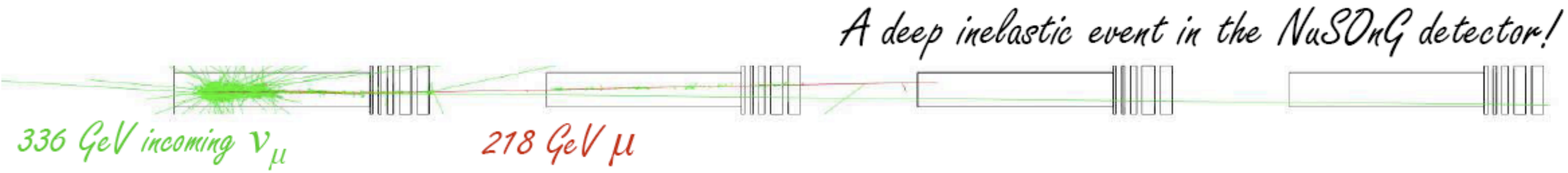
High-energy, because we'd like to use IMD events to constrain our flux prediction



4 sub-detectors:

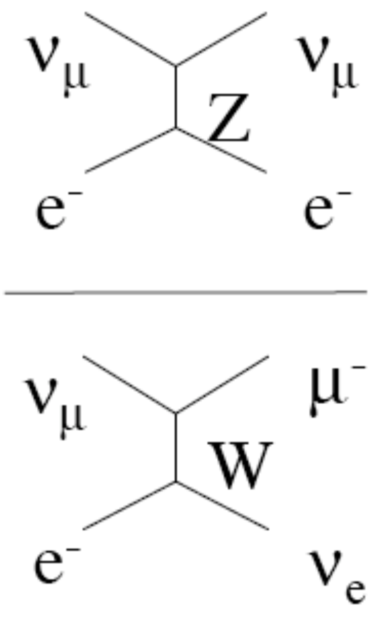


- Glass target, with 1/4 λ_0 segmentation
- Proportional chambers/Scintillator
- Muon Toroid

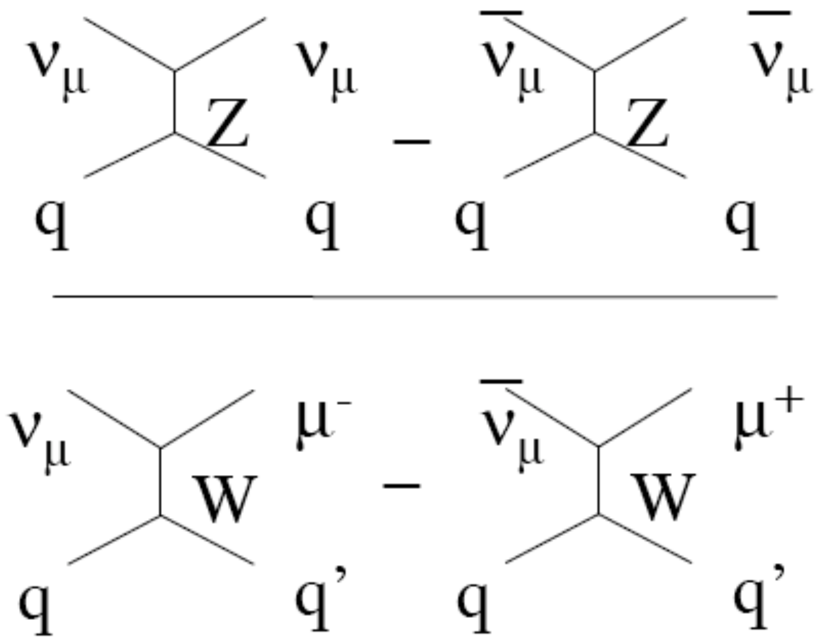


NuSOnG will work with ratios….

New!



Purely leptonic



NuTeV-style
“Paschos-Wolfenstein”

Expected errors
0.7% conservative,
0.4% best case

0.4% conservative
0.2% best case

ULTIMATE GOAL: accumulate at least an order of magnitude more neutrino events than the world's data set to date:

	# Detected to Date, All Energies, All Detectors	# Expected at NuSOnG, All Energies
$\nu_\mu, \bar{\nu}_\mu$	$< 20 \times 10^6$ (1)	$> 600 \times 10^6$
$\nu_e, \bar{\nu}_e$	$< 0.5 \times 10^6$ (2)	$> 6 \times 10^6$
$\nu_\tau, \bar{\nu}_\tau$	10	—

(1) Mostly from NuTeV, CCFR, and the MINOS near detector.

(2) Mostly from (1) above. Largest reactor neutrino data sets around few thousand events/detector. Solar neutrino experiments have recorded less than 10,000 ν_e events.

In more detail, NuSOnG will measure . . .

$\nu_\mu + e^- \to \nu_\mu + e^-$
[ES]
$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$

$\nu_\mu + e^- \to \mu^- + \nu_e$ [IMD]

$\nu_\mu + q \to \nu_\mu + X$

$\bar{\nu}_\mu + q \to \bar{\nu}_\mu + X$
[DIS]
$\nu_\mu + q \to \mu^- + X$

$\bar{\nu}_\mu + q \to \mu^+ + X$

600M	ν_μ CC Deep Inelastic Scattering
190M	ν_μ NC Deep Inelastic Scattering
75k	ν_μ electron NC elastic scatters (ES)
700k	ν_μ electron CC quasi-elastic scatters (IMD)
33M	$\bar{\nu}_\mu$ CC Deep Inelastic Scattering
12M	$\bar{\nu}_\mu$ NC Deep Inelastic Scattering
7k	$\bar{\nu}_\mu$ electron NC elastic scatters (ES)
0k	$\bar{\nu}_\mu$ electron CC quasi-elastic scatters (WSIMD)

TABLE I: Rates assumed for this paper. NC indicates "neutral current" and CC indicates "charged current."

. . . with sub-percent precision!

2. On the Physics of Neutrino – Charged Fermion Scattering

Neutrino matter scattering provides a unique an clean environment to study purely weakly interacting processes. In the Standard Model, at low enough center of mass energies, $\nu_\mu + f$ eleastic scattering is governed by the following effective Lagrangian.

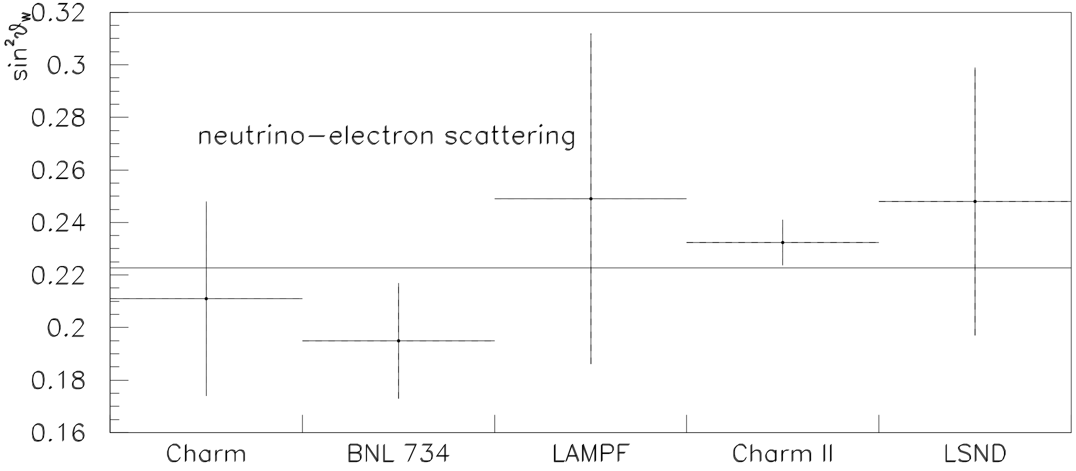
$$\mathcal{L} = -2\sqrt{2}G_F\left(g_L^\nu\,\bar{\nu}_L\gamma_\mu\nu_L\right)\times\left[g_L^f\,\bar{f}_L\gamma^\mu f_L + g_R^f\,\bar{f}_R\gamma^\mu f_R\right]$$

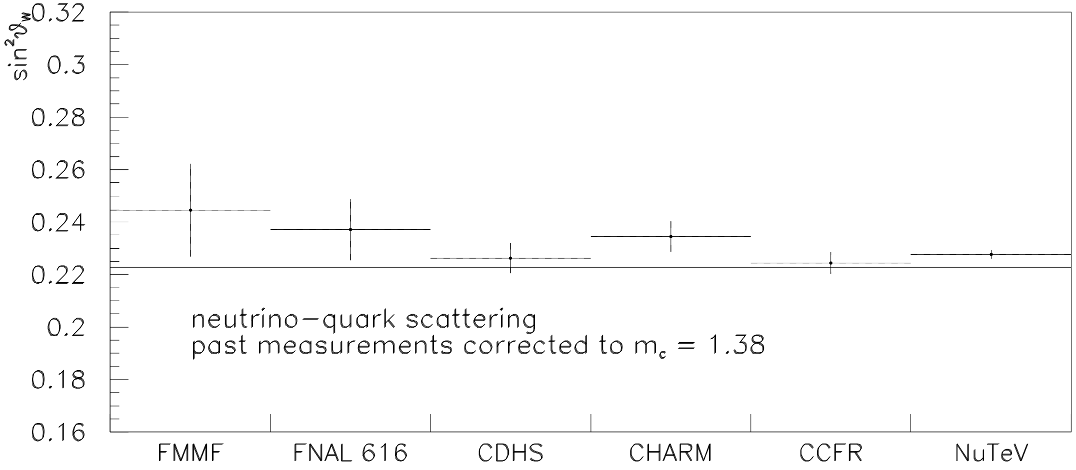
where

$$\begin{aligned} g_L^\nu &= \sqrt{\rho}\left(+\frac{1}{2}\right)\ , \\ g_L^f &= \sqrt{\rho}\left(I_3^f - Q^f\sin^2\theta_W\right)\ , \\ g_R^f &= \sqrt{\rho}\left(-Q^f\sin^2\theta_W\right)\ . \end{aligned}$$

At tree-level, $\rho = 1$. Loop corrections affect both ρ and what we mean by $\sin^2\theta_W$.

One can interpret $\nu + f$ as measuring the Weinberg angle …





… but it measures $g_L^\nu g_L^f$ and $g_L^\nu g_L^f$ independently. Much more information.

Consider four NuSOnG measurements:

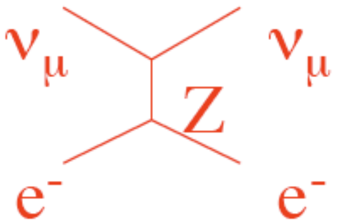
1) $\sigma(\nu, e)$,

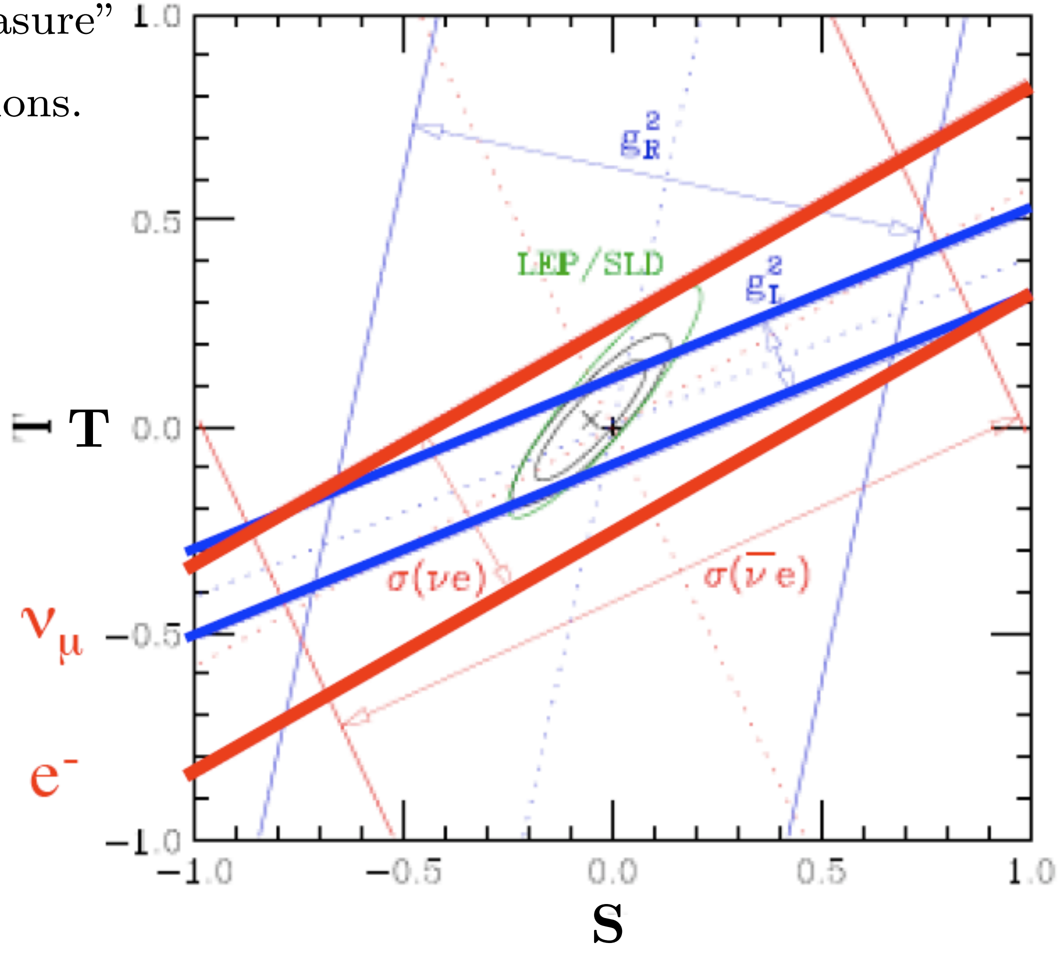
2) $\sigma(\bar{\nu}, e)$,

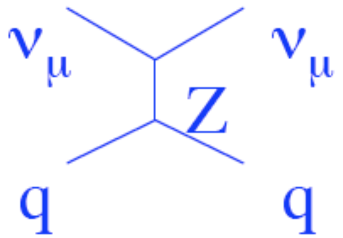
3) $$g_L^2 = (2g_L^\nu g_L^u)^2 + (2g_L^\nu g_L^d)^2 = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\right),$$

4) $$g_R^2 = (2g_L^\nu g_R^u)^2 + (2g_L^\nu g_R^d)^2 = \rho^2\left(\frac{5}{9}\sin^4\theta_W\right).$$

fix $\sin^2\theta_W$, "measure" radiative corrections.





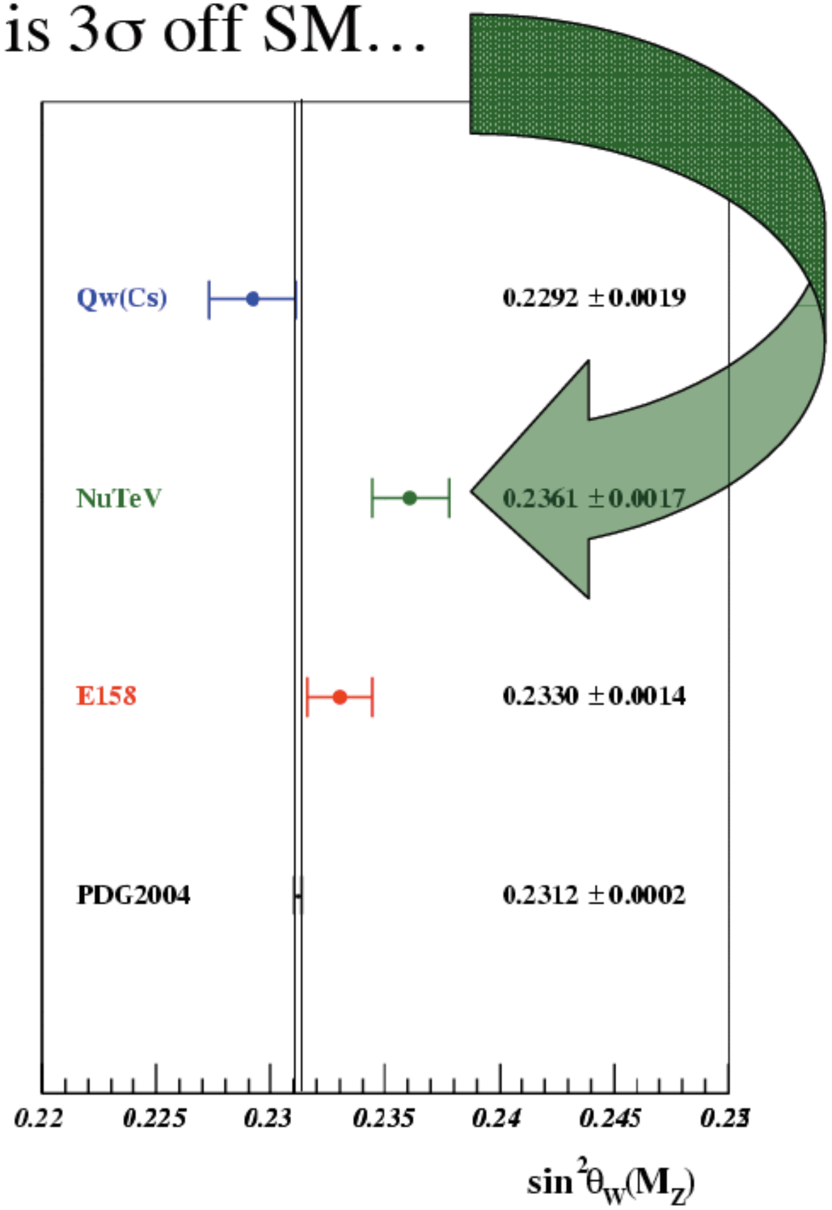


The $\sigma(\nu,e)$ and g_L^2 measurements are the strongest with the initial run-plan

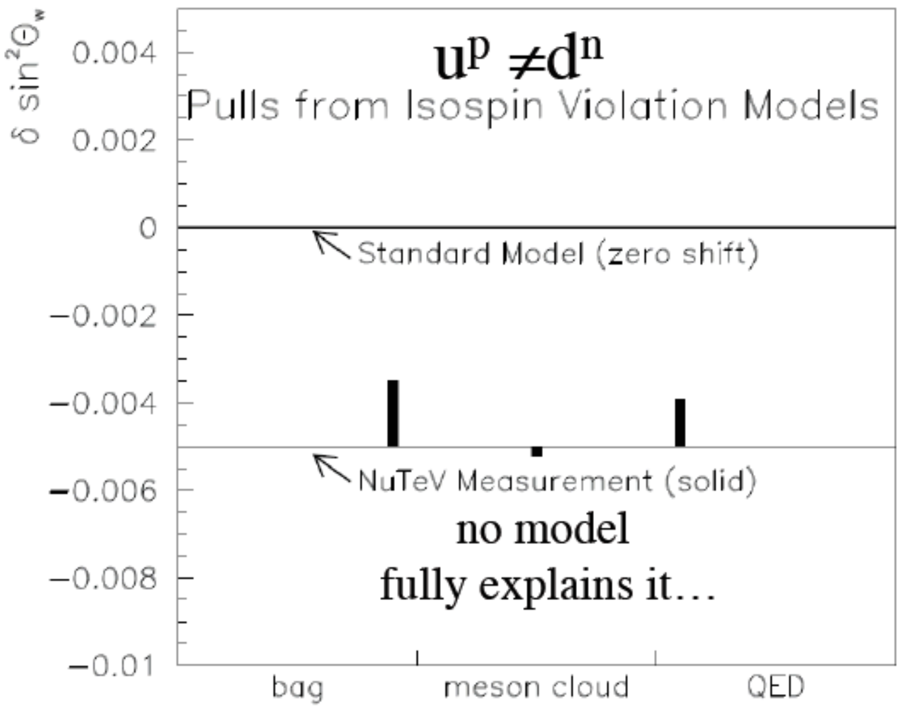
Here, I'll concentrate on $\nu_\mu + e$ elastic scattering.

- Another channel to study neutral currents with neutrinos (*cf.* NuTeV).
- Significant improvements over world's data sample – CHARM II had less than 6000 events, ν and $\bar{\nu}$ combined.
- This is a very, very clean process! (Among First Standard Model calculation, G. 't Hooft, "Predictions For Neutrino - Electron Cross-Sections In Weinberg's Model Of Weak Interactions," Phys. Lett. B **37** (1971) 195.)

NuTeV: νq scattering ("PW") is 3σ off SM…



New Physics, e.g. nonuniversality? or "Standard Model"?



An updated NuTeV analysis will be available spring/summer

3. Neutrino–Electron Elastic Scattering and New Physics

This is what one is able to measure:

$$\frac{d\sigma}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi}\left[\left(g_V^{\nu e} \pm g_A^{\nu e}\right)^2 + \left(g_V^{\nu e} \mp g_A^{\nu e}\right)^2 (1-y)^2\right] ,$$

in the limit $m_e \ll E_\nu$, for $y = \frac{T_e}{E_\nu}$ for the recoil electron. Sign ambiguity for neutrino and antineutrino scattering, respectively.

New "heavy" physics will modify the coefficents

$$g_L^\nu g_L^e = g_V^{\nu e} + g_A^{\nu e}$$
$$g_L^\nu g_L^e = g_V^{\nu e} - g_A^{\nu e}$$

Most general effective Lagrangian one can probe with $\nu_\mu + e$ scattering

$$\mathcal{L}^e_{\rm NSI} = +\frac{\sqrt{2}}{\Lambda^2}\left[\bar{\nu}_\alpha\gamma_\sigma P_L\nu_\mu\right]\left[\cos\theta\,\bar{e}\gamma^\sigma P_L e + \sin\theta\,\bar{e}\gamma^\sigma P_R e\right].$$

Λ = New Physics scale.

θ parameterizes "handedness" of the new physics. Note: signs matter.

Assumption 1: no scalar–scalar interaction ("suppressed" by neutrino and electron masses)

Assumption 2: charged current – IMD – NOT modified. This is not true of specific models

NSI reach for **neutrino-lepton scattering**

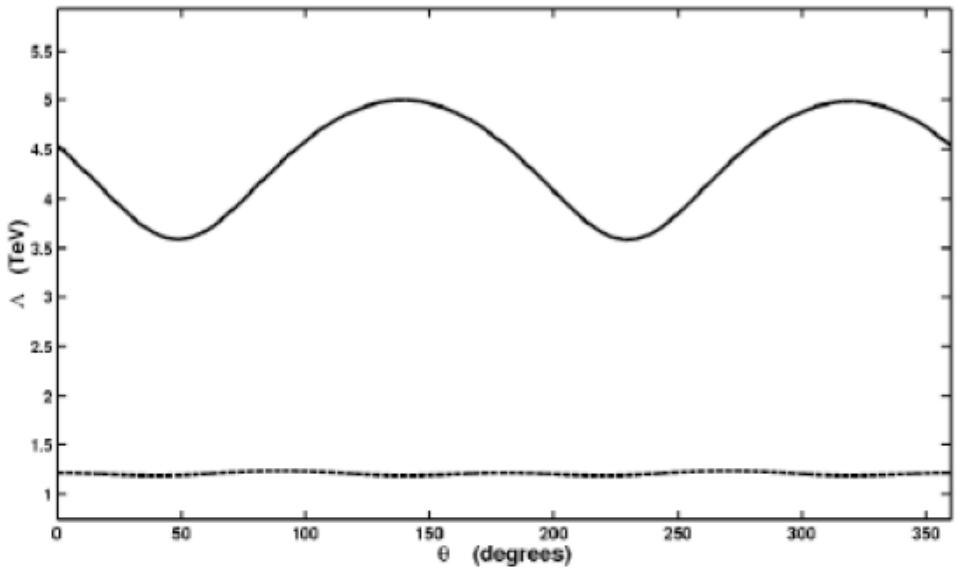
$$\mathcal{L}^e_{\rm NSI} = +\frac{\sqrt{2}}{\Lambda^2}\left[\bar{\nu}_\alpha\gamma_\sigma P_L\nu_\mu\right]\left[\cos\theta\,\bar{e}\gamma^\sigma P_L e + \sin\theta\,\bar{e}\gamma^\sigma P_R e\right]$$

mass scale

outgoing flavor

Relative mixture of handedness

Λ



θ

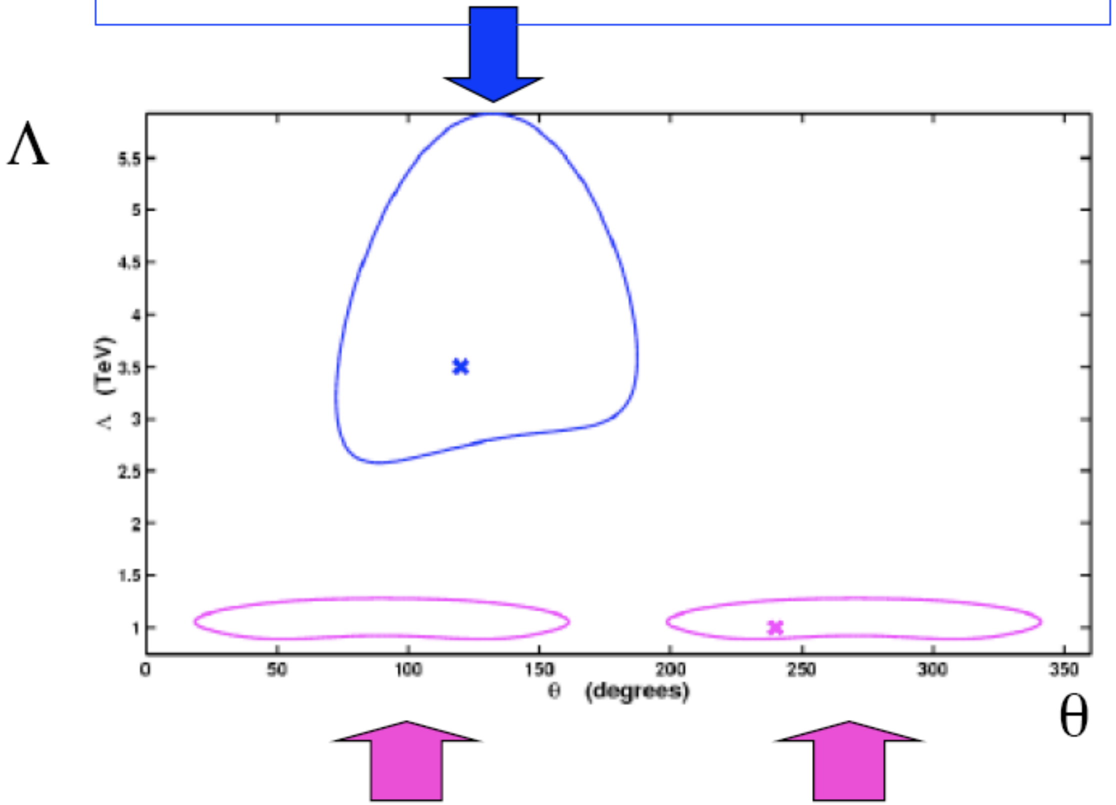
95% CL sensitivity

if α = muon flavor ~4.5 TeV

if $\alpha \neq$ muon flavor ~1.25 TeV

But we might see a signal!

Assume Λ=3.5 TeV, θ =2π/3, α=μ…
this is the 2σ contour from NuSOnG



Assume Λ=1 TeV, θ =4π/3, $\alpha\neq\mu$…
these are the 2σ contours from NuSOnG

How can we learn more about this "new physics"? We need information from other sources, including

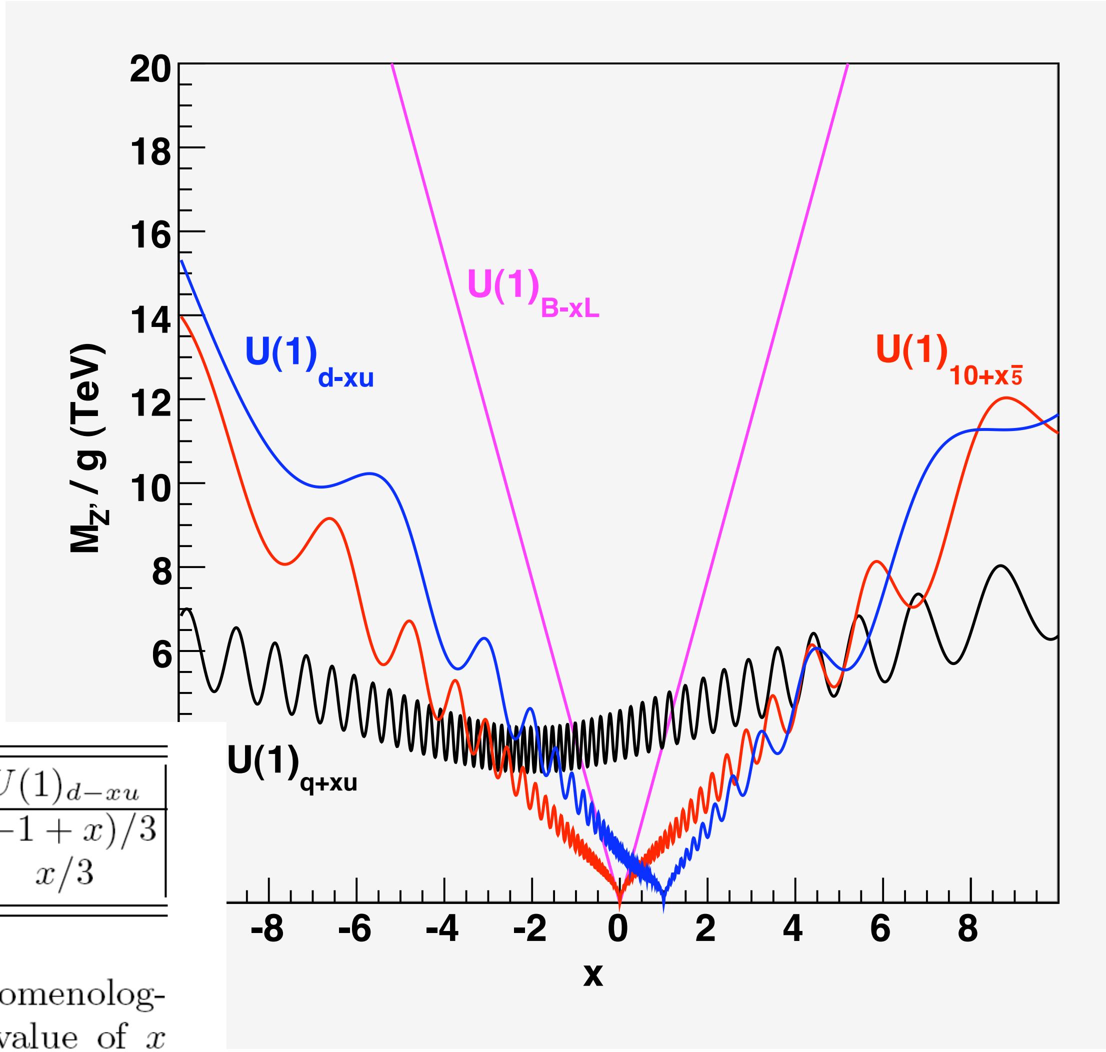
- NuSOnG neutrino quark scattering;
- Other TeV-sensitive experiments, including the LHC.

The types of new physics fall under different categories:

- They affect all "electroweak precision" observables in the same way (all loop-level effects that modify the W and Z boson propagators);
- They affect only neutrino neutral current measurements;
- They affect only neutrino-quark or neutrino-lepton measurements;
- ...

4. Some "Heavy" Examples: Z' Physics

Note: Z' couplings may depend heavily on the generation and field-type (quark versus lepton)



	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
$\nu_{\mu L}, e_L$	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	$-x$	$-(2+x)/3$	$-1/3$	$x/3$

TABLE VII: Charges of $\nu_{\mu L}, e_L, e_R$ under 4 phenomenologically viable classes of $U(1)'$ symmetries. Each value of x corresponds to a different $U(1)'$ symmetry that is considered.

[Bounds competitive with LEP]

Modifying the Neutrino Coupling to the Heavy Gauge Bosons:

- **neutrino mixing with heavy gauge-singlet leptons**

$$\begin{aligned}\nu &= \nu_{\rm light}\cos\theta + \nu_{\rm heavy}\sin\theta \\ \chi &= -\nu_{\rm light}\sin\theta + \nu_{\rm heavy}\cos\theta\end{aligned}$$

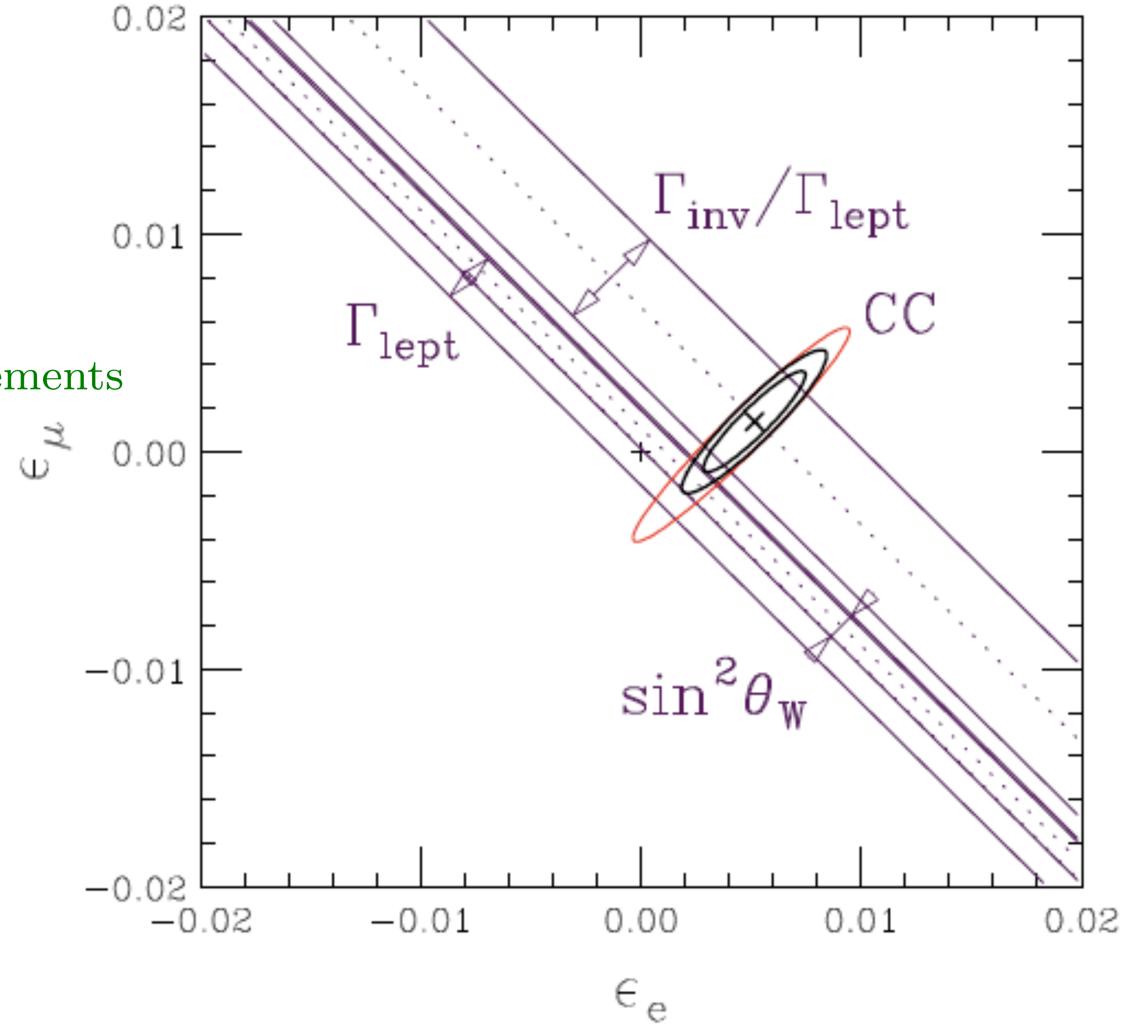
$$\begin{aligned}Z\nu\nu &= Z\nu_{\rm light}\nu_{\rm light}\cos^2\theta \\ &\quad +2Z\nu_{\rm light}\nu_{\rm heavy}\sin\theta\cos\theta \\ &\quad +Z\nu_{\rm heavy}\nu_{\rm heavy}\sin^2\theta \\ W\ell\nu &= W\ell\nu_{\rm light}\cos\theta + W\ell\nu_{\rm heavy}\sin\theta\end{aligned}$$

$$Z\nu_\ell\nu_\ell\,(1-\epsilon_\ell) \qquad W\ell\nu_\ell\left(1-\frac{\epsilon_\ell}{2}\right)$$

includes "promised" improvements

from τ data from BaBar

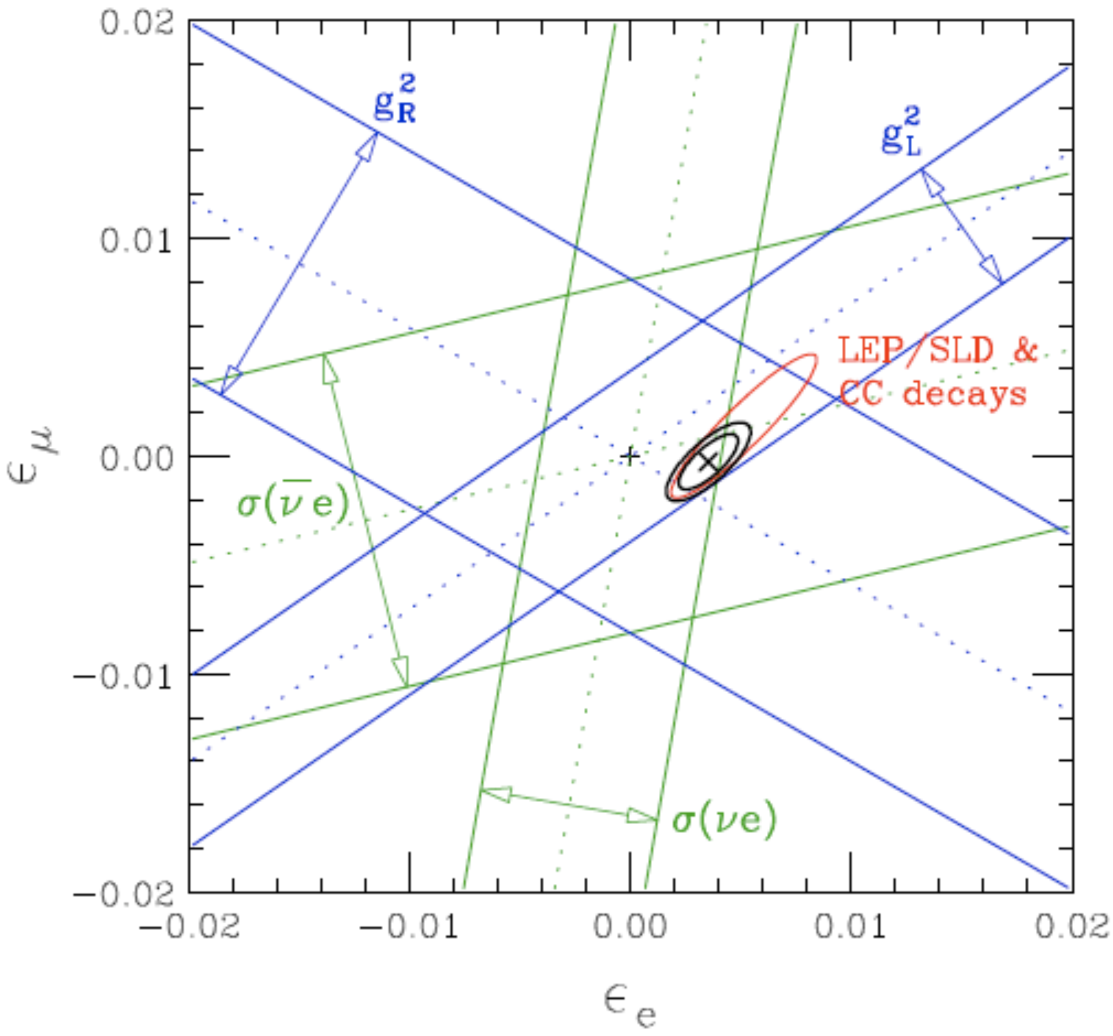
and π data from PINUE



[Loinaz *et al*, to appear]

Fit with S, T, ε_e, and ε_μ.

NuSOnG still very relevant!



[Loinaz *et al*, to appear]

Fit with S, T, ε_e, and ε_μ.

LHC:

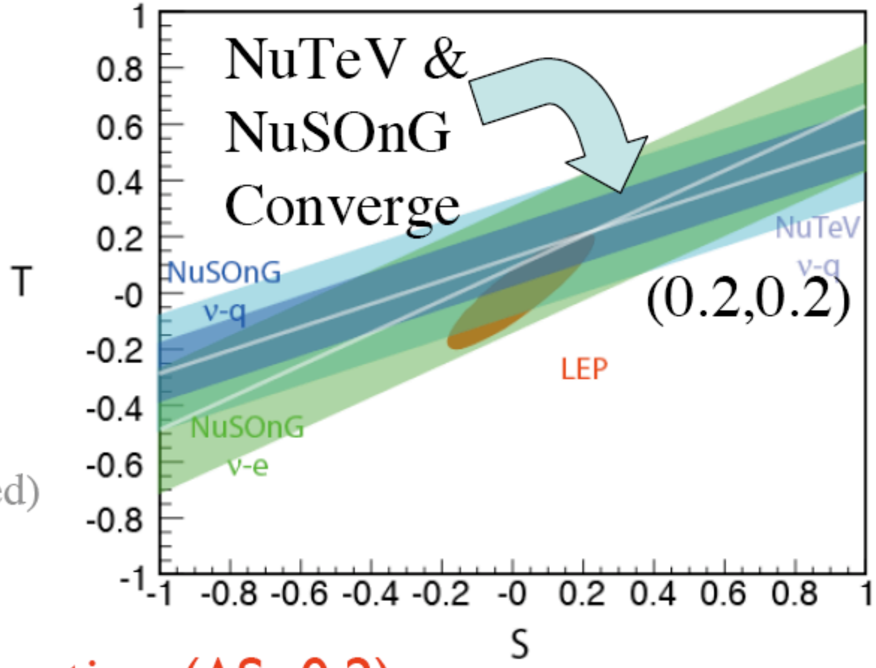
- Highly enhanced H →ZZ
- The Higgs mass,
  lets say 300 GeV
- complex decay modes
  (e.g. 6W's and 2 b's)

And what it doesn't…

- Measure mass of new quarks
- Observe new charged leptons
  (off mass shell Drell-Yan produced)
- Reconstruct the decay modes fully

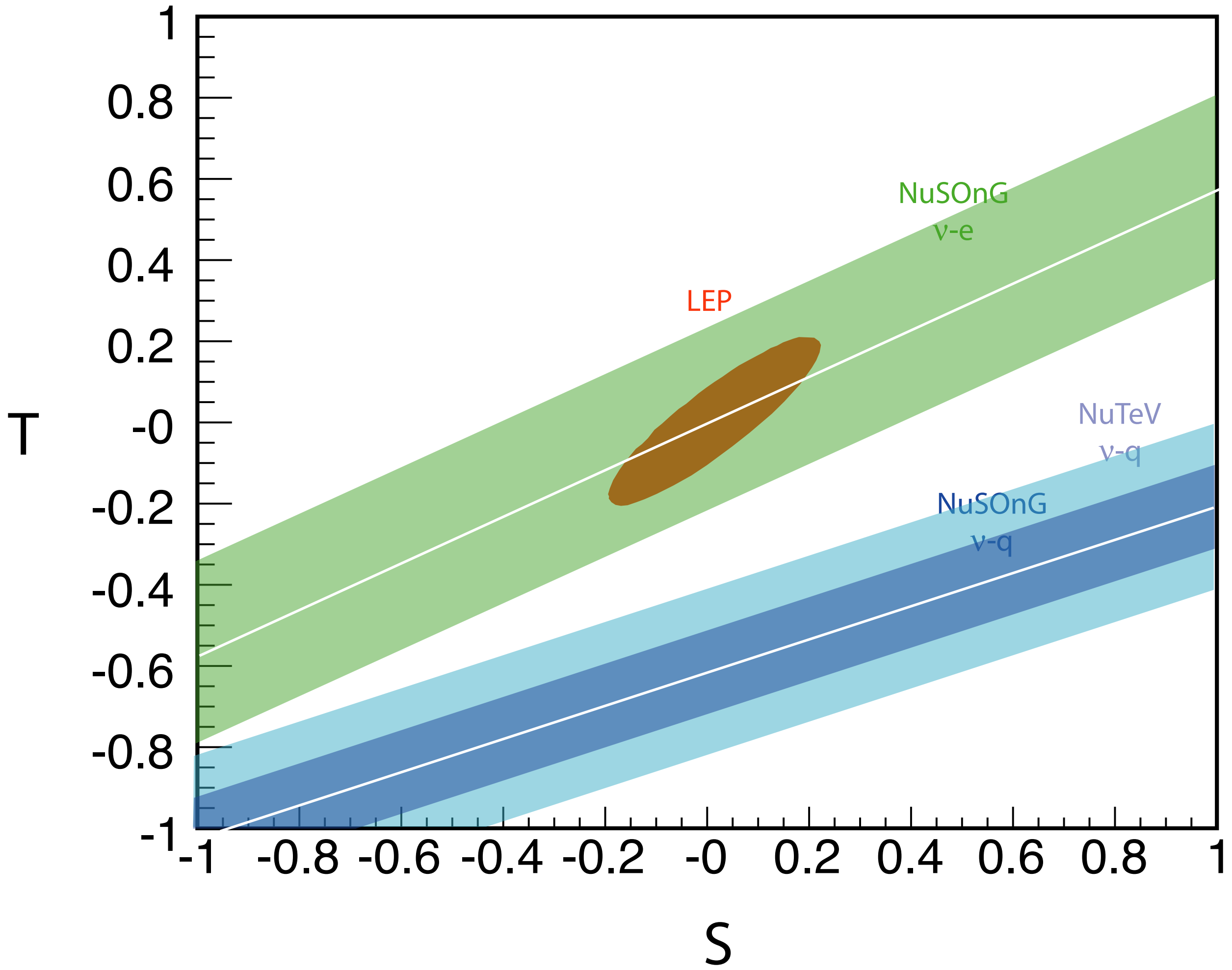
NuSOnG:

QCD explanation for NuTeV is found, allowing NuTeV to be corrected



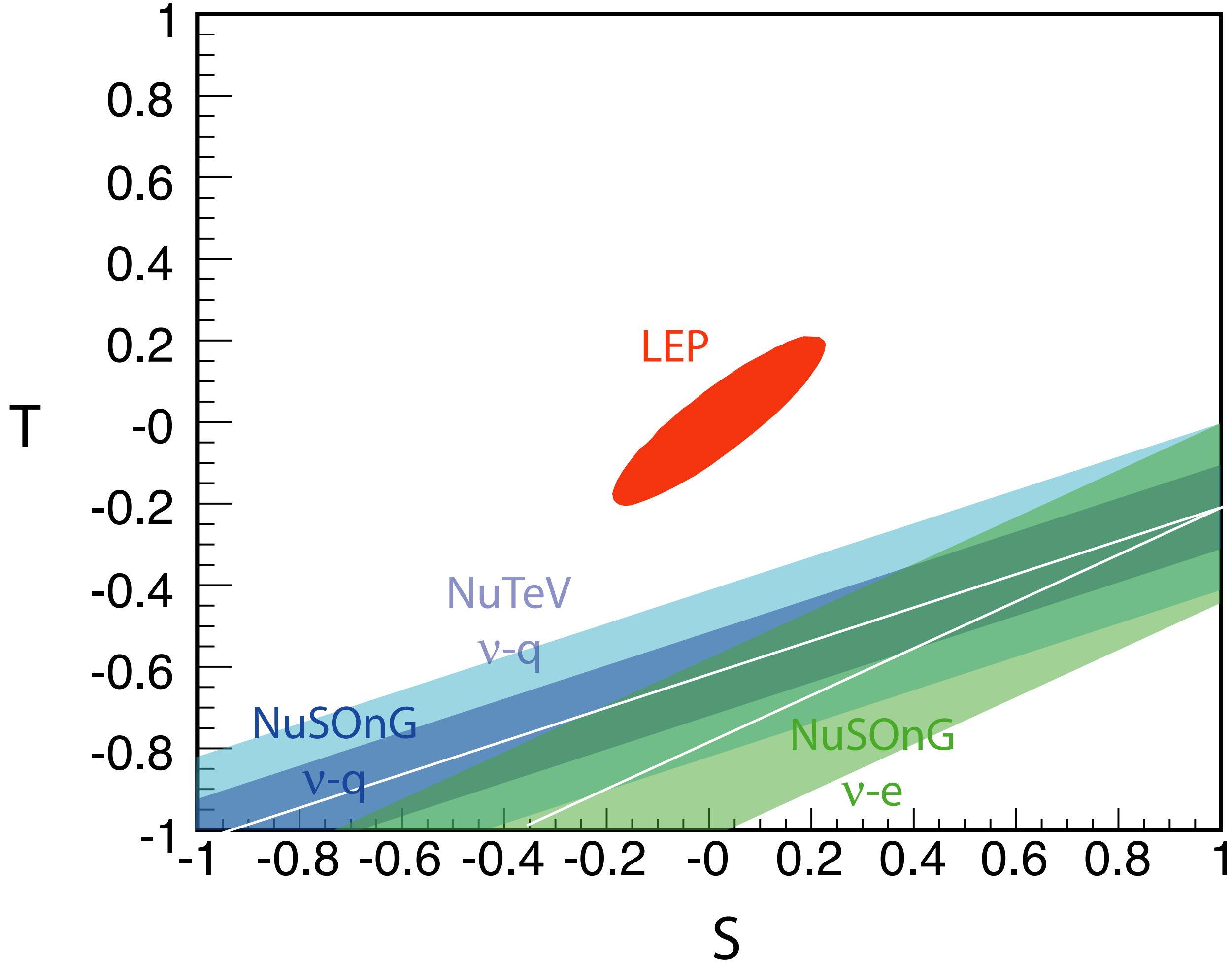
A Chiral 4th generation ($\Delta S=0.2$)
with isospin violation ($\Delta T=0.2$)

Reinforced NuTeV Anomaly: Modified Neutrino–Quark Interactions?



Lepto-Quarks!

What if The LHC Does not Find Any Evidence for TeV degrees of Freedom?

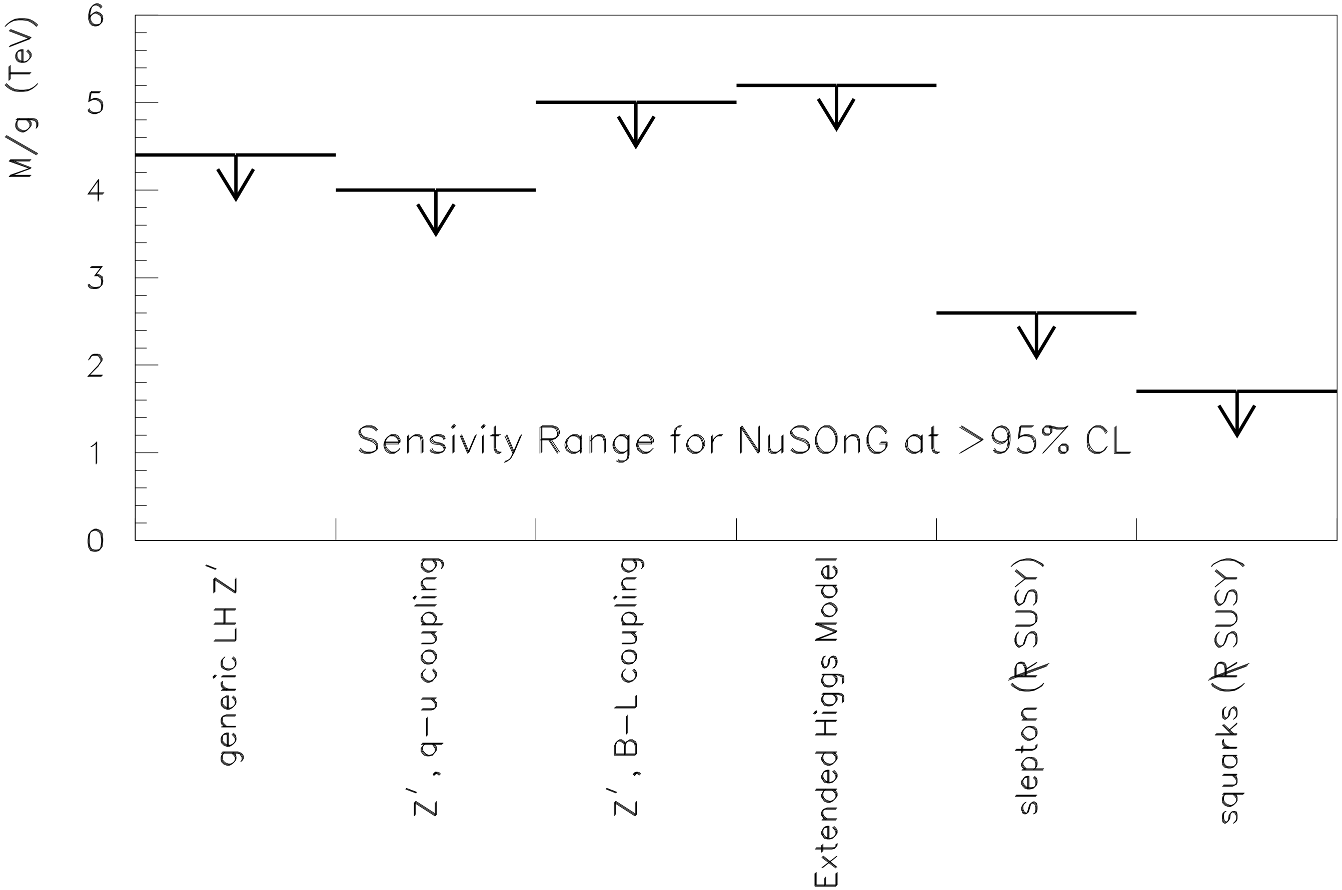


Modified $\nu - Z$ Coupling

We May Still Run Into Surprises in the Neutrino Sector (Again!)

Summary:

New Heavy Physics



Model	Contribution of NuSOnG Measurement
Typical Z' Choices: $(B-xL)$,$(q-xu)$,$(d+xu)$	At the level of, and complementary to, LEP II bounds.
Extended Higgs Sector	At the level of, and complementary to τ decay bounds.
R-parity Violating SUSY	Sensitivity to masses ~ 2 TeV at 95% CL. Improves bounds on slepton couplings by $\sim 30\%$ and on some squark couplings by factors of 3-5.
Intergenerational Leptoquarks with non-degenerate masses	Accesses unique combinations of couplings. Also accesses coupling combinations explored by π decay bounds, at a similar level.

TABLE VI: Summary of NuSOnG's contribution in the case of specific models

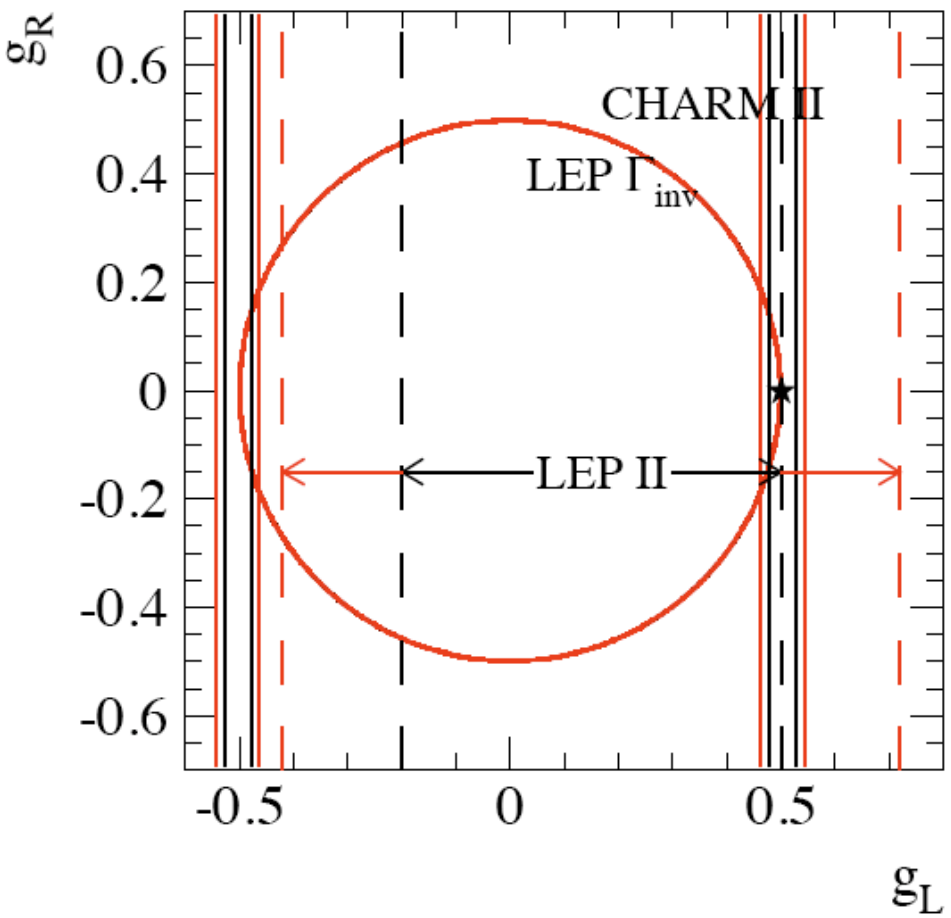
5. Another Example: The "Nature" of the $\nu - Z$-boson Coupling

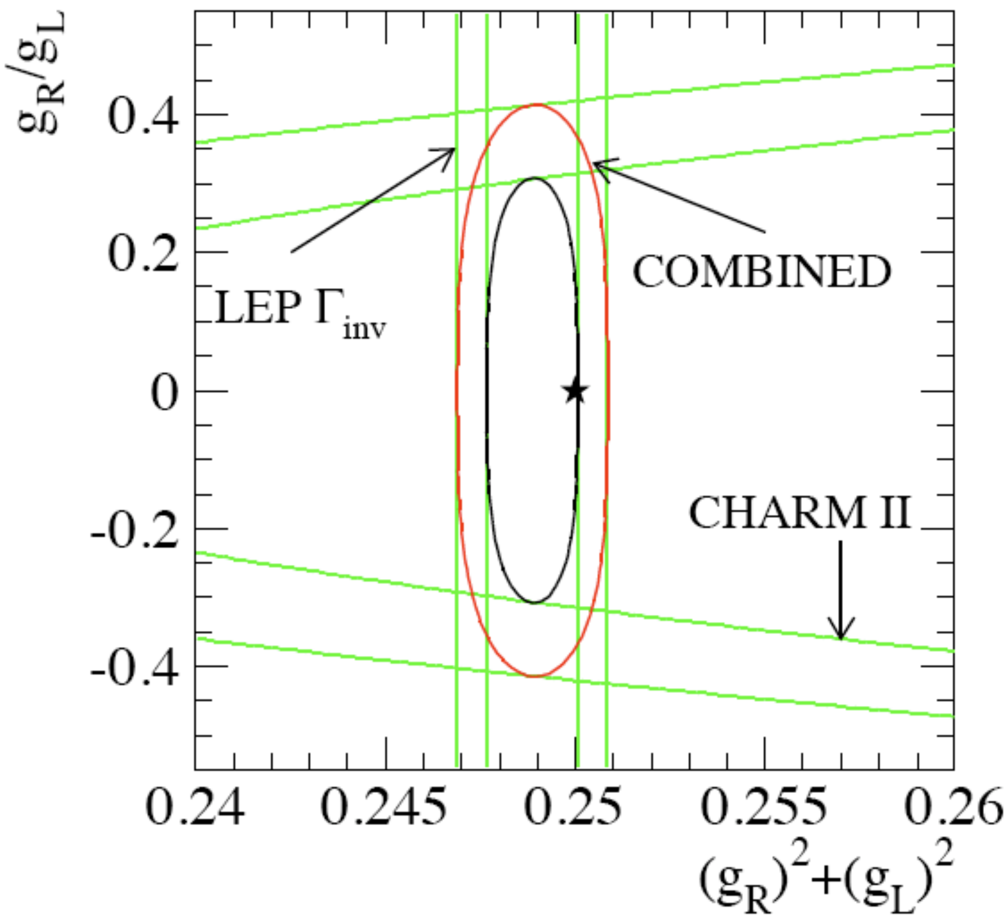
In the Standard Model, the neutrino coupling to the Z-boson is purely left-handed. It is interesting to ask "how well do we know that?"

The most precise information we have regarding the neutrino–Z-boson coupling comes from the invisible Z-width at LEP. However, LEP does not measure g_L^{ν}: it measures $(g_L^{\nu})^2 + (g_R^{\nu})^2$.

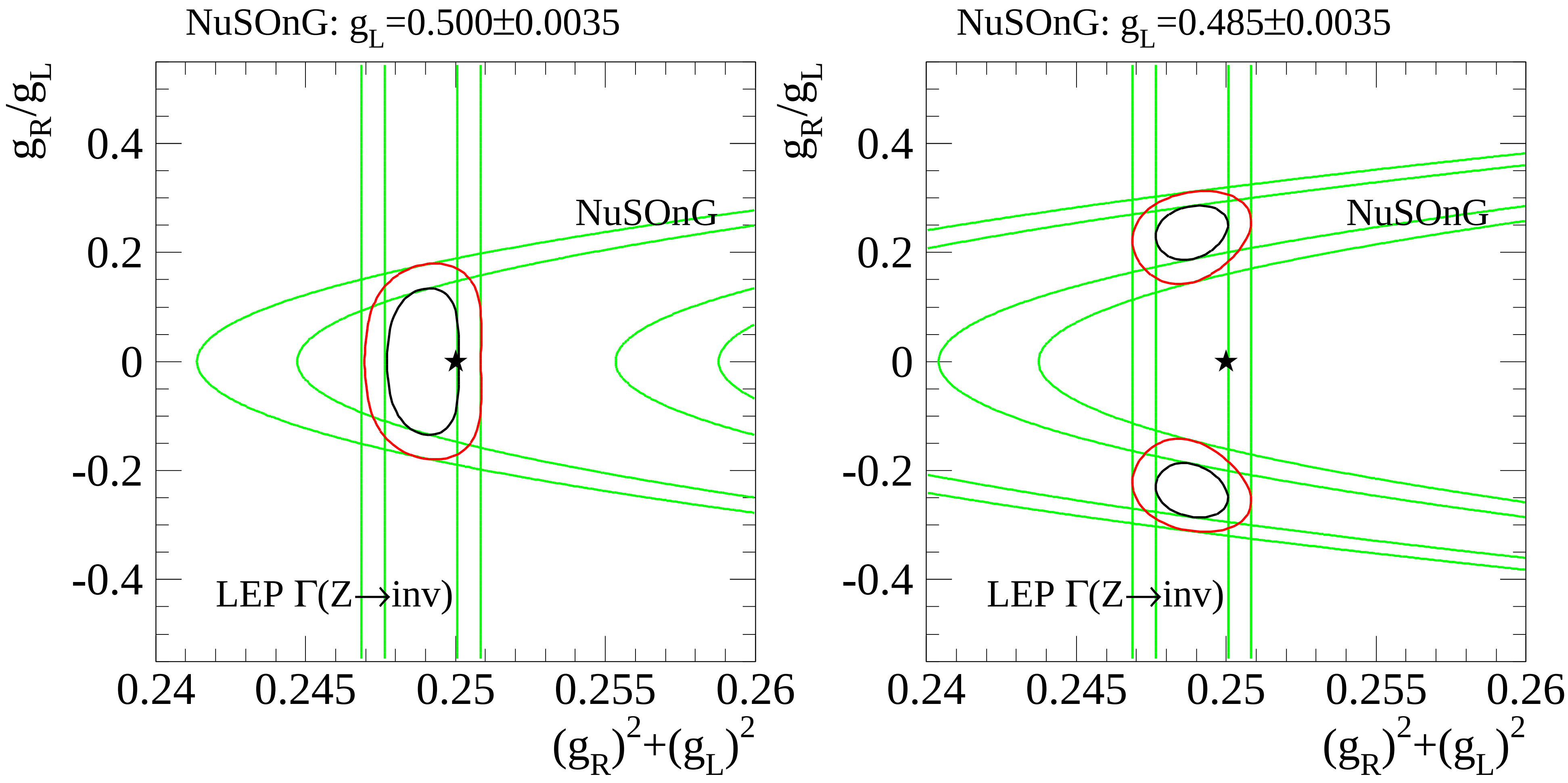
On the other hand, we know a lot about the nature of the neutrino W-boson coupling. That one is known to be purely left-handed

This means that neutrino beam experiments measure only g_L^{ν}: Complementary to LEP.





CHARM II – neutrino electron scattering – plays a fundamental role!



NuSOnG Improvement: could see new physics "easily". What kind of new Physics is this?

Competitive with E158 (Moller scattering)

$$\mathcal{L}_{\rm new} = \pm\frac{4\pi}{2\Lambda_{LL}^{\pm 2}}\left(\bar{e}_L\gamma_\mu e_L\right)\left(\bar{e}_L\gamma^\mu e_L\right) .$$

$$\Lambda^+_{LL} \geq 7\,\text{TeV}\ , \qquad \Lambda^-_{LL} \geq 16\,\text{TeV}\ .$$

[E158 only sensitive to parity-violating physics, unlike NuSOnG]

… and LEP2 $\quad \mathcal{L} = \pm\frac{4\pi}{\Lambda_{eP}^{\pm 2}}\left(\bar{e}_P\gamma_\sigma e_P\right)\left(\bar{\mu}_L\gamma^\sigma \mu_L\right)\ , \qquad P = L, R.$

	Λ^-_{eL}	Λ^+_{eL}	Λ^-_{eR}	Λ^+_{eR}
L3	3.8 TeV	8.5 TeV	2.0 TeV	6.5 TeV
OPAL	7.3 TeV	8.1 TeV	6.3 TeV	6.3 TeV
DELPHI	7.6 TeV	7.3 TeV	2.0 TeV	6.3 TeV
ALEPH	9.5 TeV	6.6 TeV	2.0 TeV	6.1 TeV

6. New Sterile Fermions and Other "Light" Physics

Nonunitarity of the 3 neutrino mixing matrix

$$\sum_j |U_{\alpha j}|^2 = 1 - X_\alpha,$$

hep-ph/0705.0107

$$P_{\alpha\alpha}^{general} = P_{\alpha\alpha}^{unitary} - 2X_\alpha[1 - 2|U_{\alpha 3}|^2 \sin^2\Delta_{31}] + X_\alpha^2.$$

L/E dependent

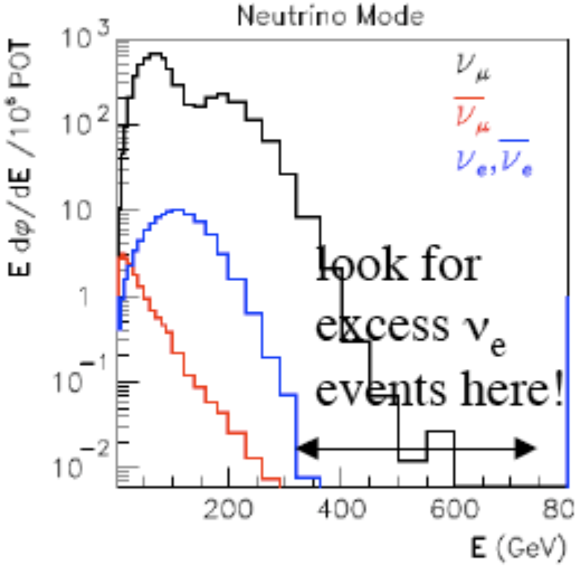
Not!

Appearance has same effect!

At L=0 there will be an instantaneous transition between neutrino species!

(Natural consequence of sterile neutrinos with masses above 100 eV)

- Look for excess ν_e's in a range not expected



To see instantaneous $\nu_\mu \rightarrow \nu_e$ look for an increase in ν_e rate at E_ν~350 GeV

Seeing both would be a striking signature!

- Look for "wrong sign" IMD

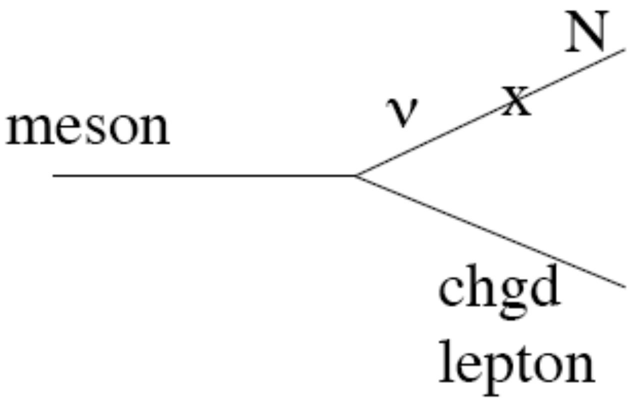
$\overline{\nu}_\mu + e^- \rightarrow \mu^- + \overline{\nu}_e$ -- this should not occur!

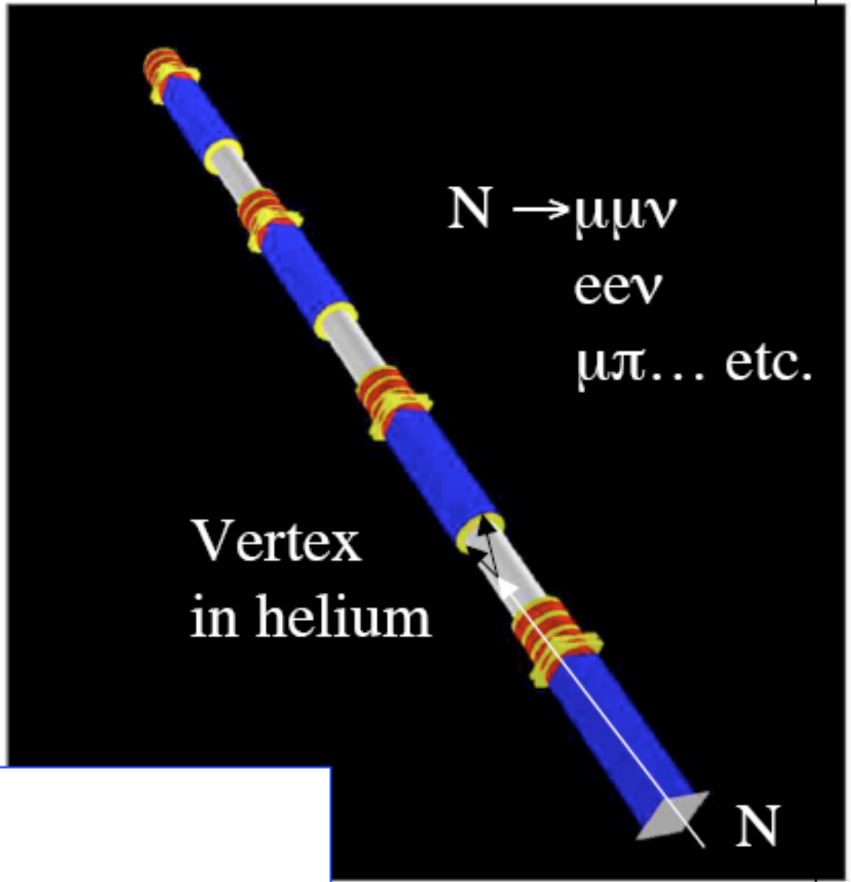
But if $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$, then $\overline{\nu}_e + e^- \rightarrow \mu^- + \overline{\nu}_\mu$ … same signature!

Unique Capability!

Also a direct search:
Filling the 15 m region between subdetectors with helium and looking for neutrissimo decays…

These are produced through mixing in meson decays:





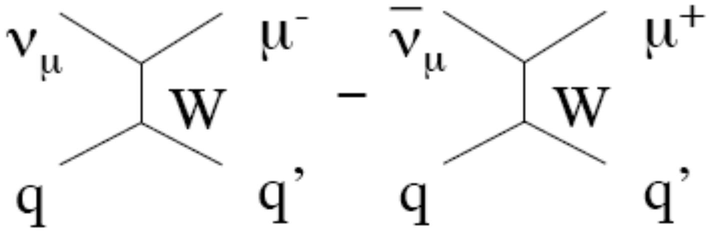
Because of the Tev-based beam, NuSOnG search for production in B-decay… i.e. up to ~ 5 GeV!

One thing I didn't talk about:

Addressing the NuTeV anomaly, and other QCD related matters:

The question…

Is this:



being modeled correctly?

NuTeV measures the parton distributions on iron, with these assumptions:

1. $F_2^{\nu} = F_2^{\bar{\nu}}$
2. R_L from charged lepton scattering applies to ν and $\bar{\nu}$

Our goal on NuSOnG:
A global fit to F_2^{ν}, $F_2^{\bar{\nu}}$, xF_3^{ν}, $xF_3^{\bar{\nu}}$, R_L^{ν}, $R_L^{\bar{\nu}}$

We are investigating our capability

(Technique was developed by CCFR student C. McNulty, which was limited by statistics.)

Summary and Conclusions

- A large, well-understood sample of $\nu_\mu + e$ ES events should prove to be a powerful tool for exploring TeV scale new physics. NuSOnG aims at at least an order of magnitude more events than all previous neutrino experiments combined.
- Any new physics result at NuSOnG should prove to be complementary to anything we may discover at the LHC – including ony a standard model Higgs boson! NuSOnG will likely help elucidate the nature of the new physics discovered at the LHC.
- By measuring $\nu_\mu + e$, NuSOnG can test most new physics interpretations of the NuTeV anomaly.
- Along with a record number of $\nu_\mu + e$ ES events, one also gets a record number of $\nu_\mu + q$ DIS events.
- These will allow one to test all standard model solutions to the NuTeV anomaly, plus perform several key QCD measurements (structure functions, etc).

- Even if there is no new physics, NuSOnG explores a different sector of the Standard Model and contributes significantly to electroweak precision observables and QCD. But remember: neutrinos have been (very) good to particle physics in the past!
- An experiment like NuSOnG can only be performed at Fermilab. No one else has the Tevatron accelerator!
- NuSOnG would serve as a great flagship experiment for a next-generation of Tevatron-based fixed target experiments.

	# Detected to Date, All Energies, All Detectors	# Expected at NuSOnG, All Energies
$\nu_\mu, \bar{\nu}_\mu$	$< 20 \times 10^6$ (1)	$> 600 \times 10^6$
$\nu_e, \bar{\nu}_e$	$< 0.5 \times 10^6$ (2)	$> 6 \times 10^6$
$\nu_\tau, \bar{\nu}_\tau$	10	OPPORTUNITY?